

**A THEORY OF HUMAN ERROR\***

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**SUMMARY**

Human errors tend to be treated in terms of clinical and anecdotal descriptions, from which remedial measures are difficult to derive. Correction of the sources of human error requires that one attempt to reconstruct underlying and contributing causes of error from the circumstantial causes cited in official investigative reports. A comprehensive analytical theory of the cause-effect relationships governing propagation of human error is indispensable to a reconstruction of the underlying and contributing causes. This paper highlights a validated analytical theory of the input-output behavior of human operators involving manual control, communication, supervisory, and monitoring tasks which are relevant to aviation, maritime, automotive, and process control operations. This theory of behavior, both appropriate and inappropriate, provides an insightful basis for investigating, classifying, and quantifying the needed cause-effect relationships governing propagation of human error.

**INTRODUCTION**

Human error is of major concern in the development and deployment of man/machine systems. Human error is a significant contributing factor in aviation, maritime, automotive, and process control accidents. Thus the alleviation in number and consequence of human errors should be a primary goal of man/machine systems research. Traditionally, however, human error has been treated only tangentially. The measurement of task or system errors has routinely been employed in man/machine studies as a performance metric in the evaluation of other variables (e.g., equipment design, training, etc.). Human error has also been used in clinical and anecdotal terms as a convenient classification in accident investigations. Developing remedial measures from these applications is difficult, however, as errors have not always been classified according to a consistent structure; and other contributing factors or prevailing conditions have not been noted.

Recent research focusing directly on the nature and classification of human errors is changing the above state of affairs, however. Singleton (Refs. 1 and 2) has reviewed classification schemes, analytical techniques, and psychological theories in the study of human error. More recently Norman (Refs. 3 and 4) has been investigating applied human information processing and has evolved an action theory which he has used in the

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classification of errors made by highly-skilled operators in complex, high-demand systems. Most recently we have finished a report for NASA (Ref. 5) in which several behavioral models were reviewed for use in subsequent studies of human errors in aviation operations. These models cover continuous and discrete control, supervisory control, monitoring, and decision making and provide a basis for diagnostic investigation as well as research.

Human error is a complex, multifaceted phenomenon. In accounting for human error in complex man-machine systems we must consider both the spontaneous errors or "slips" dealt with in Norman's action theory (Ref. 4) and more rational errors (having an assignable cause in hindsight) which arise due to problems in detection, perception, recognition, and judgment. The distinction here is that in one case the spontaneous error is seemingly aberrant and unintentional, whereas other errors can presumably be rationalized with behavioral theories that account for perception, judgment, decision making, monitoring, detection and recognition, and manual control.

#### DEFINITIONS

In previous work by Beek, et al. (Ref. 6) human error has been defined as an inconsistency with a *pre-defined behavioral pattern* established by virtue of system requirements and specifications and the design of the equipment and procedures to meet those specifications. This is a practical operational definition; however, it should be noted that incidents and accidents can arise because of inadequacies in the *design* of equipment and procedures. Errors may also be precipitated by environmental stress (physiological and psychological) impinging on the human operator. This has led us to differentiate between the *sources* and *causes* of human error. *Sources* are internal to the human operator and their consequences should be measurable as changes from normal or ideal human behavior which is consistent with system requirements. *Causes* are external factors which induce undesirable deviations in human behavior, such as unexpectedly large or extreme disturbances, high workload, distractions, inaccurate or noisy information, illusions, equipment design deficiencies, and inadequate training.

Accompanying the current trend towards increasing automation in man-machine systems, there is increasing concern for errors induced by man-machine interaction (Ref. 7). In some cases errors are induced by increased complexity — the man-machine interface — and in other cases the operator's less active role as a monitor and supervisor seems to be the problem because there is a degradation of skill. At issue here is what the optimal level of operator involvement should be and the structuring of this involvement in order to minimize the occurrence and influence of human error on system performance.

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\* There could, of course, be internal causes of human error such as psychophysiological or neurological impairments. These should be handled with proper selection and periodic screening procedures which are not of direct interest here.

Errors or mismatches between desired and actual system or subsystem outputs are essential in situations where feedback is involved as an operating principle. Most of the time human operators use these errors to advantage in performing as error-correcting rather than error-avoiding system elements. For this reason in operations involving aviation, maritime, and automotive traffic control and process control, the errors per se are of major concern only when they are undesirable because of their size, timing, or character. These errors, which are intolerable in one way or another, we shall call *grievous errors*. In general, a *grievous error will involve an exceedence of safe operating tolerances*.

Human errors that do not always result in grievous errors may be nearly impossible to measure in practice unless behavioral identification techniques are employed. Behavioral identification may be performed by qualified observers (Refs. 8, 9, and 10) or by signal correlation analysis which can partition human error into coherent and incoherent components. Such identification of human errors which may be inconspicuous in one situation is very important, for they may lead to grievous errors in other circumstances. Thorough analyses of mission phase behavior sequences, both normal and abnormal, are necessary prerequisites to the application of behavioral identification techniques in the study of human error. Before considering some of the sources and causes of human error, we shall discuss the buildup of mission phase behavior sequences from constituent task behavior.

## BUILDUP OF MISSION PHASE BEHAVIOR SEQUENCE(S) FROM CONSTITUENT TASK BEHAVIOR

### A Perceptually Centered Viewpoint for Task Behavior

For a particular task the human component(s) as input-output elements consist of one (or more) of the pathways illustrated by Fig. 1 for one among several human operators of a system. Here the system inputs and errors may appear in several sensory modalities, and the motor subsystem output may be manipulative or verbal. The pathway used in a particular circumstance is the result of the nature of the perceptual field and of training. Table 1 summarizes these and other facets of this perceptually centered model of human behavior.

The human's operations are thus defined as an open-loop, closed-loop, or open- and closed-loop behavior pattern with identified sensory input and motor output modalities. For some inputs, of course, there is no immediate output; instead, the information received may simply be stored in memory. In other cases the lack of a measurable output should nonetheless be interpreted as the 0 portion of a 0,1 binary pair of possibilities.

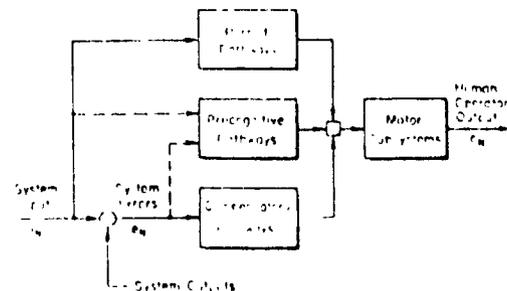


Figure 1. Three Paths in Perceptually Centered Model of Human Behavior

TABLE 1. SUMMARY CHARACTERISTICS OF PATHWAYS IN PERCEPTUALLY-CENTERED MODEL OF HUMAN BEHAVIOR

PATHWAYS SELECTED	PERCEPTUAL FIELD CONTENT	ACTION OR OUTPUT	CORRELATES OF TRANSITION AMONG LEVELS OF SCP
Compensatory	Narrow; deviations only	Designed to correct exceedences and reversals; not necessarily rehearsed	
Pursuit	Broader; separable inputs, outputs, commands, disturbances in addition to deviations	Designed to correct deviations and to compensate for internal delay; moderately well rehearsed	
Precognitive	Exceedingly broad and extended, even among other individuals and organizations by means of a conference, by recall of past experience, or by recruitment of other resources; separable inputs, outputs, commands, disturbances only; feedbacks not necessary	Discrete; cued, transient; very well rehearsed	

**Monitoring and Decision Making Viewpoint for Task Behavior**

With increased use of automatic controls and computers in modern day aircraft, traffic, and process control systems, the role of the human operator is becoming more supervisory, involving increased amounts of monitoring and decision making. In these roles, human outputs are typically discrete (as opposed to continuous control actions) and include verbal communication as well. Monitoring and decision making errors can arise due to misperception of monitored information and misinterpretation of perceived information. Errors can also occur in the more cognitive aspects of decision making where the operator must account for various possible consequences of the alternative actions available to him.

Monitoring and decision making constructs and viewpoints are useful in several ways. First, human errors sometimes appear to be inexplicable when, for example, only two courses of action are possible, and an operator appears to make the obviously wrong choice. By considering the elements of these task situations in a decision making context, one can gain additional insight into the underlying factors involved. Second, if specific analytic decision-making models are appropriate descriptors of the mission phases being examined, then the model can serve as a means for the analysis and interpretation of the operational or experimental results. Third, a combination of monitoring, decision making, and control viewpoints is essential in treating repeated trials in an experiment or an ensemble of simulations involving many crews. In a single trial, behavior and performance for all the tasks involved are specific concrete actions (or inactions) flowing in a sequence. Error is identified as an extreme deviation from a desired state. Among many trials these concrete actions often exhibit differences, either in kind or in degree. A probabilistic structure for particular events then becomes appropriate as a means of describing the experimental data. Further, the potential tradeoffs (based on experience and training) involved in selecting various emergency actions

can be exposed in the light of a utility concept. Monitoring and decision making theories are the appropriate vehicles for such considerations.

### **Partition of the Mission into Phases, Tasks, Skills, and Outcomes**

If we are to apply these elementary behavioral models to complex operations of men and machines, they must be associated with sequences of operations which, together, serve to accomplish a desirable end, i.e., a mission. To accomplish this the mission is first defined and partitioned into a hierarchy of constituents. The primary constituents are *mission phases*. These are of a size and duration which allow the broadest factors (e.g., environmental variables) that influence human behavior to be identified. At the next level are *tasks*, which are associated with a particular operation in a sequence and are sized to permit the identification of "critical" skills. Aberrations in the execution of these skills ultimately determine the sources of contributions to human error.

A mission phase may be broken down into various subdivisions depending upon its complexity. For our purposes here we are ultimately interested in the elemental unit of all phases involving the human operator, the *task*. As a working definition here we will define a task as *an activity at the functional interface of the human operator and the individuals, objects, and environments with whom or which he interacts* (adapted from Ref. 11). We will further specify a task for our purposes here as a goal- or criterion-oriented work increment involving application of a *skill* or *set of skills* by the human operator. Thus, by partitioning the mission phases into tasks, we can then identify those fundamental human operator behavioral factors, *skills*, which influence operational safety. For tasks which are critical to safety (i.e., exert a predominant influence in some sense), it is the *proficiency* with which a skill or set of skills is applied that we wish to consider in order to identify the underlying sources of human error.

In preparing the operations breakdown for a particular mission phase, each task for each operator is listed as an item in an ordered, nominal sequence. Conceivably this order might be changed or omitted in off-nominal circumstances, and this by itself may be a cause of error. Associated with each task are input and output modalities for each operator in his respective relationships with other operators and equipment. Associated also with each task is an indication of the human behavior characteristics nominally involved in carrying out the task at hand. In many cases the nominal behavioral characteristics may not be exhibited by actual operators, and abnormal behavior may result in an out-of-tolerance system error.

For the study of human error, the nominal task breakdown must therefore be further subdivided to account for all possible *outcomes* induced by abnormal behavior. In this endeavor the application of Murphy's law and its corollaries can be helpful. Other off-nominal aspects which should be considered are the accumulation of stress and degradation of skill. Each mission phase presents a combination of *environmental* and *task* stresses on the operators, and these stresses influence operator performance. After lapses in operational practice or long intervals of inactivity, individuals have to cope with the problem of maintaining proficiency of skills which may be critical to safety. Skills performed *infrequently*, for whatever reason, are most likely to fall into this category. Of these skills, those having

high workload factors by virtue of being time-constrained or because they involve complex operations are most likely to cause serious performance decrements. Several conditions may contribute to the degradation of these skills: (a) lack of practice, (b) inability to practice in the appropriate environment, (c) interference or negative transfer arising from the practice of competing skills, and (d) physiological deconditioning due to fatigue induced by the environment or due to alcohol or drug stresses. The tasks which are most likely to be affected by these human conditions should be especially flagged for investigation.

In most of the tasks where precognitive operations are identified as nominal or customary, additional qualification is necessary. Such open-loop operations are normally of limited duration and are properly interspersed or concluded with closed-loop operations either directly, as in dual mode continuous control, or indirectly in the context of an off-line supervisory monitor. Omission of the closed-loop monitoring activity may in fact lead to human error as shown in Ref. 12. To examine the role of a supervisory monitor in more detail, we next consider some models for the integration of the three functional pathways in Fig. 1.

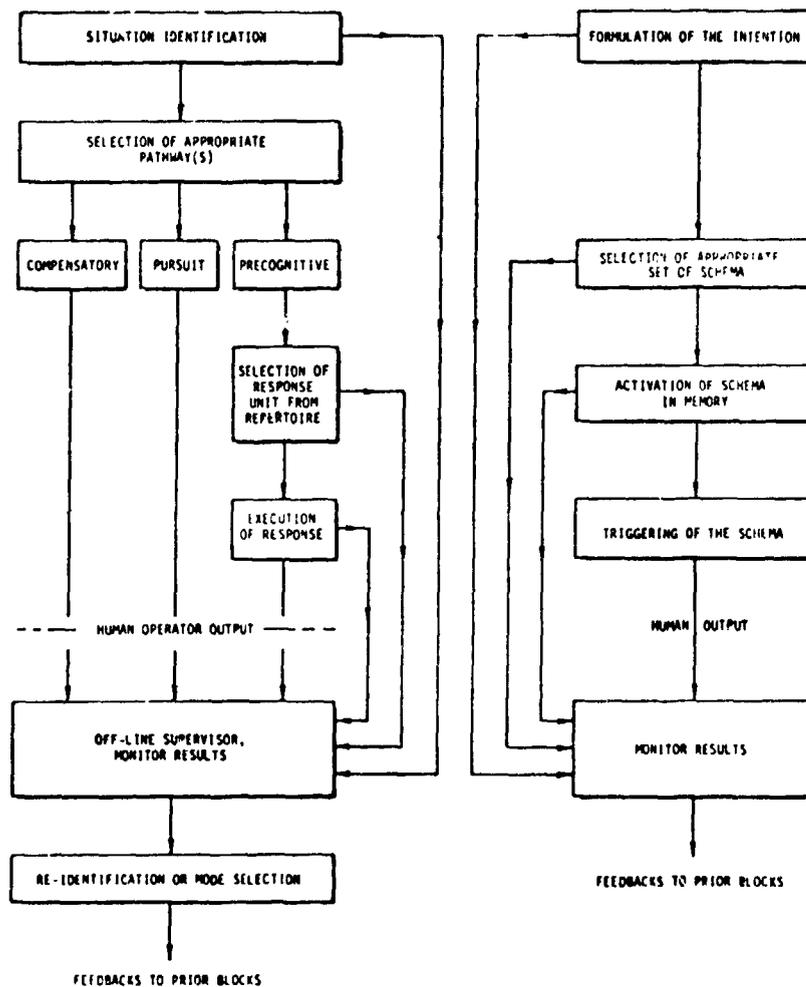
#### INTEGRATION OF THE PATHWAYS — THE METACONTROLLER

Each pathway in Fig. 1 contains a number of subsets of behavior appropriate to the task. Assume that identifiable prerequisite conditions and limits can be found (e.g., experimentally) for each subset of observed behavior. Then one model for the perceptual organization process would be an active off-line supervisory monitor which identifies the conditions that currently exist, selects and activates some most likely pathway/subset, monitors the result, reselects a new pathway/subset when necessary or when further information is identified as a result of the first operations, and so forth. Appropriately this has been termed the metacontrol\* system by Sheridan in Ref. 13. A simplified diagram of such a metacontroller is given in Fig. 2a. Other preliminary work on an algorithmic-type model for the successive organization of perception (SOP) process is given in Ref. 14. The possibilities for error due to inappropriate activities within such a system are manifold. Such a model provides a logical basis for understanding some of the causes underlying selection of an inappropriate behavioral model which may ultimately lead to an identifiable error.

An appropriate form for this model is a flow or decision process algorithm. Related models have been described in Refs. 16 and 17, and applied to a specified task involving a given sequence of subtasks in Refs. 18 through 21. Thus the algorithmic approach is by no means novel. Most of these attempts have had limited application because of the inordinate complexity and repetitive cycling required to represent continuous tasks. Yet by breaking out the compensatory and pursuit pathways as separate entities which handle most of the continuous operations, the metacontroller of

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\* Metacontrol = the human's activity-supervising control, transcending the various directly involved systems such as the perceptual, central, and neuromuscular systems (from Greek "meta" meaning "involved with changes").



a) Simplified Metaccontroller for Successive Organization of Perception

b) "Theory of Action," Ref. 15

Figure 2. Flow Diagram for SOP Operations and the Ref. 15 Theory of Action

Fig. 2a gets around some of these problems. Algorithmic models are used where they are best suited (logical functions), while isomorphic models of human behavior are used where they are most efficient (well-defined tracking or stimulus-response situations). Continuing research in the disciplines of observation, pattern recognition, estimation, and timeshared processing should yield additional material useful to the interpretation of SOP. For example, Noton offers a sequential pattern perception and recognition theory in Ref. 22 which appears to have connections with SOP and other models which have been found useful in characterizing human behavior.

A particularly interesting parallel to the SOP metaccontroller which is especially valuable for the understanding of error is given in Ref. 15. The "Theory of Action" proposed there has a number of cognitive stages and components. The base stores for action are organized memory units or sensorimotor knowledge structures — "schemas" which control skilled action sequences. A basic control sequence starts with intention, and proceeds through selection, activation, and triggering of schema to result in an output action. The results at various levels in this sequence are monitored, and may be modified by feedbacks to the previous stages. A simplified block diagram for this theory is shown in Fig. 2b. Its elements are clearly similar to the precognitive elements in the metaccontroller of

Fig. 2a. Much of the Fig. 2b model is based on the study of verbal "slips," which can be errors by another name; so the connections between human manual control and verbal activities are very useful in our search for generalization.

Using this overall structure as a point of departure, we progress in the next topic to discuss some sources and causes of human error.

### SOURCES AND CAUSES OF HUMAN ERROR

The functional pathway triad and metacontroller model for human behavior illustrated in Fig. 2a contains within its structure many features which can, in abnormal versions, lead to grievous system errors. These features we shall refer to as *sources* or *antecedents* of error. Sources are endogenous or internal to the human. Their consequences are all measurable in terms of changes from ideal or nominal human behavior for a particular task. These changes may be induced by external (exogenous) factors which will be referred to as *causes* of errors. The first two columns of Table 2 illustrate these distinctions for compensatory operations.

The remaining two columns of Table 2 present a verbal synthesis of a great deal of empirical data from many experimenters. All of the currently demonstrated forms of abnormal compensatory input-output behavior are represented here. In total they represent an error source which can be described generally as *inappropriate perception, decision, and/or execution within a selected level (in this case, compensatory) of organization of behavior*. The sources of error in this framework are summarized in Table 3.

In principle tables similar to Table 2 can be constructed for the other source possibilities in Table 3, e.g., Table 4 for pursuit operations. However the experimental data base for most of these is nowhere near as comprehensive as it is for the compensatory pathway. Many of the elements in the precognitive pathway can be developed, by analogy, from Table 1 of Ref. 15, which lists the presumed sources of "slips" (or errors) in the structure of Fig. 2b.

Transitions from higher to lower levels of skill occur when the attentional field becomes too narrow. They can also occur when the human is sufficiently impaired perceptually (i.e., by alcohol, fatigue, hypoxia, etc.) so that action as a multi-channel operator is significantly degraded. In these instances divided attention is possible only by switching to and fro as an essentially single channel information processing device.

Although probably one of the most fundamental sources of human error, the inappropriate *organization* of perception and behavior for the task at the executive level of the metacontroller has received much less attention in the literature than have inappropriate perception, decision, and/or execution *within* a selected level of behavioral organization. The SOP theory described in Ref. 23 offers a unifying approach to inappropriate *organization* as a source of human error.

TABLE 2. BEHAVIORAL SOURCES OF ERROR IN COMPENSATORY SYSTEMS

SINGLE CHANNEL OPERATIONS

BASIC SOURCE (ENDOGENOUS)	CAUSES (EXOGENOUS)	OPERATOR BEHAVIOR	EFFECTS ON SYSTEM
Extreme command or disturbance amplitudes	Unexpectedly large command or extreme environment	Operator response normal	System overloaded, forced out of tolerance although operating properly
Extreme command or disturbance bandwidth	Broadband input signal noise; Unexpectedly broadband disturbance	Regression of crossover frequency	Reduced system bandwidth
Controlled-element change	Malfunctor/failure in controlled element	Affecting output for transient interval; Adaptation to new controlled element	Transient errors during transition; Reduced system bandwidth
Reduced attention field	Poor signal/noise ratio (e.g., poor contrast, high intensity distraction stimuli, low level signals, etc.)	Operator threshold, net gain reduction	System bandwidth reduction; (missed signals as one extreme)
Reversals	Misperception of error sign; Naivety	Remnant increase; Intermittently reversed output	Increased system noise; Intermittently reversed system output

MULTI-INPUT OPERATIONS

BASIC SOURCE (ENDOGENOUS)	CAUSES (EXOGENOUS)	OPERATOR BEHAVIOR	EFFECTS ON SYSTEM
Reduced attention, perceptual scanning	Increased informational requirements for monitoring or control  Information overload: Too many separate input channels; Too many significant signals; Backlog of unattended operations	Remnant increase (scanning); Increase in loop gains; Simultaneous multi-channel operations  As above, plus failure to detect some signals, increased latencies, and missed output responses	Increased system noise; Reduced bandwidth  Distortions; Missed responses; Inhibitory or the other square wave
Reduced attentional field	Operator impairment (fatigue, alcohol, hypoxia, etc.)	Remnant increase over scanning; further decrease in loop gain; sequentially-switched single channel operations; selection/missed responses	Increased system noise Reduced bandwidths Increased latencies Missed responses
Illusions, kinetosis	Conflict between or among visual, vestibular, aural, kinesthetic and/or proprioceptive inputs	Remnant increase; Decrease in operator's gain; Mal a propos responses; Missed responses	Increased system noise Reduced bandwidth Mal a propos responses Missed responses

CONCLUSIONS

The input-output behavior of human operators in manual control systems is characterized by an internal organization involving three major pathways. These correspond to closed-loop, combined open- and closed-loop, and open-loop behavior patterns. In manual control systems which exemplify these patterns, the system bandwidths, attentional fields, and rehearsal requirements are ordered correspondingly, i.e., compensatory < pursuit < precognitive. Similar but inverted orderings of perceptual motor loading and system latencies are associated with the three pathways.

### TABLE 3. SOURCES OF HUMAN ERROR

(Sources are endogenous or internal to the human operator by definition)

Inappropriate perception, decision, and/or execution within a selected level of behavioral organization

Compensatory (expanded in Table 2)  
Pursuit (expanded in Table 4)  
Precognitive (expanded in Table 1 of Ref. 15)

Selection of response unit  
Execution of response

Transitions from a higher to lower level of behavioral organization

Precognitive to pursuit  
Precognitive to compensatory  
Pursuit to compensatory

Inappropriate organization of perception and behavior for the task at the executive level of the metacontroller

(Items 1-5 are associated with the "situation identification" block in Fig. 2a)

Errors in:

- (1) Formulation of intent, assignment of function and its priority
- (2) Identification of specific task/situation/action - continuous or discrete
- (3a) Selection of likely sources of information and their temporal order (i.e., past, current, or preview)
- (3b) Assignment of priority in sources of information among inputs and feedbacks
- (4) Identifying predictability or coherence in and among sources of information
- (5) Identifying familiarity with the task

(Item 6 is associated with the "selection of appropriate pathway(s)" in Fig. 2a)

- (6) Organizing operation on inputs and feedbacks.

Inadequate off-line monitor/supervisor in the metacontroller

The three-pathway model for manual control can be generalized to a perceptually-centered model appropriate for input-output human behavior involving sensory modalities other than vision and output modalities other than manipulation.

The perceptually-centered model for human behavior is further generalized to include an executive and supervisory-monitoring metacontroller which identifies the situation, selects the appropriate pathway, directs the information flow through the pathway selected, and monitors, on an off-line basis, the resulting outputs. The off-line monitoring feature constitutes yet another feedback, albeit on an intermittent and longer term basis.

The characterization of human behavior presented here provides a rational basis for planning specific investigations of the sources of human error, either for the purpose of research in advance or diagnosis after the fact. When the purpose and scope of an investigation has been set forth, the behavioral models summarized here can be used to predict (sometimes), subsume, describe, and rationalize the experimental or operational results.

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TABLE 4. BEHAVIORAL SOURCES OF ERROR IN PURSUIT OPERATIONS  
(Multi-Input Operations, by Definition)

BASIC SOURCE (ENDOGENOUS)	CAUSE (EXOGENOUS)	OPERATOR BEHAVIOR	EFFECTS ON SYSTEM
Controlled element change	(see corresponding causes in Table 2)	Transient regression to compensatory level (see corresponding behavior in Table 2)	Transient errors during transition; Reduced system bandwidth
Divided attention, perceptual scanning	(see corresponding causes in Table 2)	Remnant increase; Decrease in operator's gain; (see also corresponding behavior in Table 2)	Increased system noise; Reduced bandwidth; (see also corresponding effects in Table 2)
Reduced attentional field in spatial dimensions	Poor input and/or error signal/noise ratio (e.g., inability to identify input. Task involves disturbance regulation rather than command-following and disturbance cannot be identified); Mismatched scaling between input and error; Distortion of input; Lack of input conformability with visual field; See also corresponding causes in Table 2	Remnant increase; Operator's threshold on input may cause missed responses and regression to compensatory level; Operator's threshold on error may reduce gain in or open compensatory loop (see also corresponding behavior in Table 2)	Increased system noise; Reduced system bandwidth (missed responses as one extreme)
Reduced attentional field in temporal dimension, i.e., reduced preview	Inability to identify future input or disturbance; Prodigious extrapolation required to estimate future input or disturbance	As above, plus increased latencies	As above, plus increased response latencies
Reversals	Perceptual inversion of input; Faulty input-background discrimination; Lack of input conformability with visual field	Remnant increase; Intermittently reversed output	Increased system noise; Intermittently reversed output
Illusions, kinesthetics	(see corresponding causes in Table 2)	Remnant increase; Decrease in operator's gain; Mal a propos responses; Missed responses	Increased system noise; Reduced bandwidth; Mal a propos responses; Missed responses

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